High-Efficiency L-band T/R Module: Development Results

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***Abstract* – Future interferometric synthetic aperture radar (InSAR) systems require electronically scanned phased-array antennas, where the transmit/receive (T/R) module is a key component. The T/R module efficiency is a critical figure of merit and has direct implications on the power dissipation and power generation requirements of the system. Significant improvements in the efficiency of the T/R module will make SAR missions more feasible and affordable. The results of two high-efficiency T/R modules are presented, each based on different power amplifier technologies. One module uses a 30W GaAs Class-A/B power amplifier and the second module uses a 70W LD-MOS Class-E/F power amplifier, where both modules use a common low power section. Each module operates over an 80MHz bandwidth at L-band (1.2GHz) with an overall module efficiency greater than 58%. We will present the results of these two T/R modules that have been designed, built and tested.**

I. Introduction

Recent advances in the scientific understanding of the solid-Earth's crustal deformation have been made possible using InSAR techniques to provide centimeter-level surface displacement measurements at fine resolution. L-band repeat-pass InSAR techniques have been shown to provide very accurate and systematic measurements of surface deformation and surface strain accumulation due to seismic and volcanic activity. The L-band wavelength (1.25GHz) provides the ability to make these measurements under a variety of topographic and land cover conditions, day or night, with wide coverage at fine resolution and with minimal temporal decorrelation.

The T/R module described in this paper is a critical component in L-band SAR instruments which can be traced to missions found on the NASA strategic roadmaps. Repeat-pass InSAR measurements of Earth surface-displacement are at the foundation of the NASA roadmap for "Solid Earth" science. Because of the great benefits an orbital InSAR capability offers for the study of Earth crustal dynamics, ice sheet motion, volcanism, and other surface-change phenomena, an InSAR mission has been deemed the highest priority for Solid Earth science at NASA [1-2].

A. Project Description

In this project, a product line of high-efficiency L-band T/R modules has been developed for use in L-band InSAR missions. To achieve high efficiencies at high output powers, we have investigated the use of Class-E/F power amplifiers. The Class-E/F power amplifier delivers 70W RF power at L-band. We have also developed a 30W T/R module using a Class-A/B power amplifier. The overall efficiency for both the 30W and 70W T/R module exceeds 58%. Current state-of-the-art T/R modules can only achieve moderate efficiencies of 30-40% at L-band.

II. T/R Module Topology

The T/R module architecture is shown in Fig. 1 where the only difference between the 30W and 70W module is the power amplifier (PA) stage. The module includes a common phase shifter and variable attenuator, a 3W driver amplifier to drive the PA and the low noise amplifier (LNA) on receive. A low-loss high-power circulator at the antenna port provides sufficient isolation between transmit and receive channels. Solid state switches are used at the low power input section. The T/R module is controlled by a Xilinx 4005XL field programmable gate array (FPGA) which controls the module amplitude and phase, generates the receiver and transmitter timing window, and measures the ambient temperature.

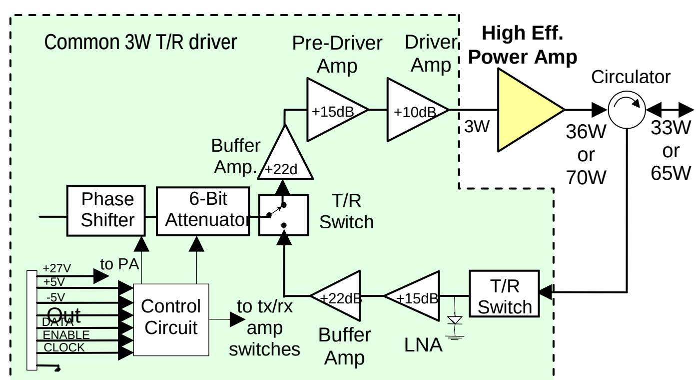

Fig. 1. Block diagram of the L-band T/R module. The 30W Class-A/B or 70W Class-E/F PA is the final power amplifier in the transmit chain.

The work described in this paper are the results of a three-year task sponsored by the NASA Earth-Sun System Technology Office (ESTO) under the Advanced Component Technology (ACT) program, Award No. ACT-02-0017, "Ultra-High Efficiency L-band T/R Modules for Large Aperture Scanning Antennas".

At the heart of the T/R module is the high-efficiency power amplifier (PA) where it serves as the last stage in the transmit chain. The efficiency of this PA for the most part determines the overall efficiency of the T/R module. We have developed two different power amplifiers, each with the same drive level such that either PA can be substituted into the same T/R module architecture. The first T/R module uses a 30W Class-A/B PA using GaAs FET devices. The second module uses a 70W Class-E/F switching amplifier using LD-MOS devices. Switching amplifiers (e.g., Class-D, E, E/F, F) have only recently been exploited as RF amplifiers due to the availability of transistors with substantial gain and power at microwave frequencies [3-5].

A. LD-MOS Push-Pull Class-E/F Power Amplifier

We have selected the Class-E/F circuit topology for the 70W T/R module. Fig. 2 shows a simplified schematic of the push-pull amplifier optimized for a Class-E/$F_{odd,2}$ operation [6-7]. The amplifier uses a pair of transistors driven as switches 180-degrees out of phase. It incorporates two baluns to make single-ended to differential-ended conversion and impedance transformation. To achieve a high coupling coefficient and good balance, a broadside multilayer coupling structure is used as the balun. This novel balun circuit results in higher efficiency, higher operating frequency and wider bandwidth in a very compact layout [8]. The input and output matching circuit models incorporate the significant package inductance and output capacitance of the power transistors, which was critical to achieving operation at 1.2GHz. A multistage input matching circuit was implemented to increase bandwidth. At the output of the amplifier, the inductance of the balun and the output capacitance of the transistor are tuned to form a parallel resonance LC tank at the operating frequency of the amplifier. The second harmonic trap, implemented as part of the drain bias circuit, helps shape the current waveform and also reduced the second-harmonic of the output power spectrum, resulting in increased efficiency. The circuit uses a low-loss, low-dielectric constant substrate material. Low frequency stabilization circuits were implemented for unconditional stability [9].

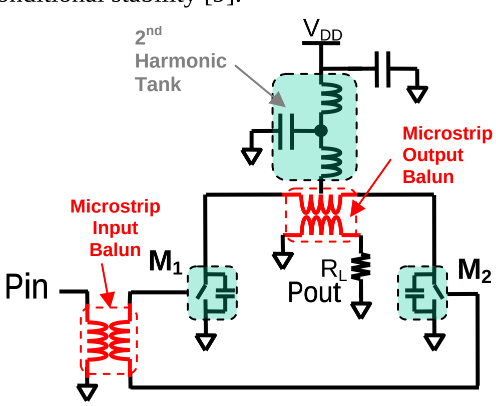

Fig. 2. Simplified schematic of the Class-E/F power amplifier.

B. GaAs Push-Pull Class-A/B Power Amplifier

The 30W PA consists of a GaAs Class-A/B power amplifier as shown in the simplified schematic in Fig. 3. The amplifier incorporates an active gate bias circuit for improved power output in saturation. The input and output matching networks have been optimized for our frequency of operation (1.2-1.3GHz). The design also incorporates ultra-low Equivalent Series Resistance (ESR) capacitors for low loss matching.

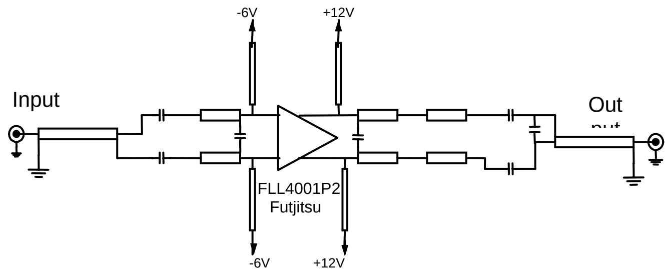

Fig. 3. Simplified schematic of the Class-A/B power amplifier.

III. Results

We will present the results of the 30W and 70W power amplifiers and the results of the integrated 30W and 70W T/R modules.

A. Results of the 70W Class-E/F Power Amplifier

A push-pull Class-E/F PA was designed using the compact, low-loss impedance-transforming microstrip baluns (Fig. 4). The circuit dimensions are 3.5cm x 5.0cm. The amplifier uses a pair of Motorola 284 LD-MOS transistors.

The broadside multi-layer coupling balun was implemented using two strips of metal inductors overlayed on top of each other with a 5-mil dielectric layer between inductors. The broadside coupler has a coupling coefficient of k=0.75 (compared to k<0.5 for an interdigital coupling structure). The balun has excellent balance in magnitude and phase over a broad frequency range [8].

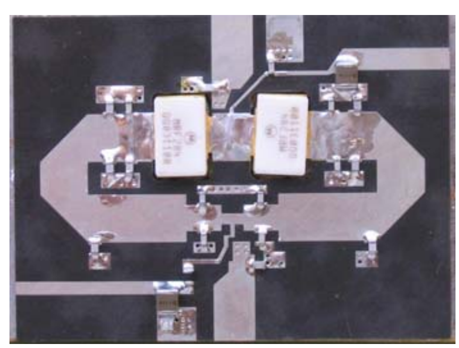

Fig. 4. Photograph of the LDMOS Push-Pull Class-E/F power amplifier with broadside coupling balun.

We improved the modeling of the active devices and passive elements of the amplifier resulting in more accurate input and output matching circuits and have added stabilization circuits. Fig. 5 shows the operating frequency of the amplifier centered at 1.2 GHz. The amplifier has 12 dB gain with a 1-dB bandwidth of 170MHz. Using the 3W T/R module driver at 1.21 GHz, the PA achieved 56W with a peak power added efficiency (PAE) of 65%. Fig. 6 shows that at 1.21 GHz, a maximum output power of 74W and peak PAE of 67% was achieved (72% drain efficiency). Table 1 compares the performance of the Class-E/F power amplifier with other recently reported switching amplifiers [10-12].

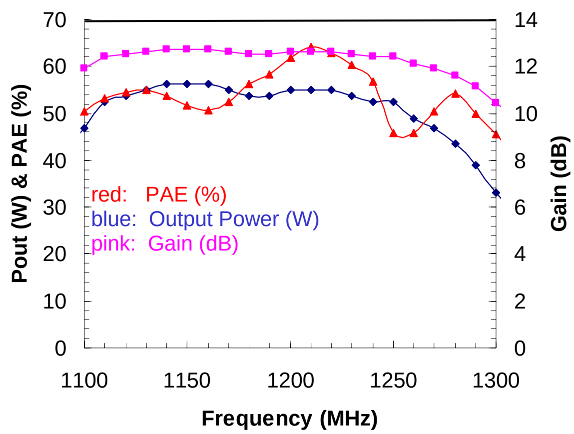

Fig. 5. Power, gain and PAE of Class-E/F PA. Input Power: 3W, Peak PAE: 65%, Peak Power: 56 W. At least 33W output power from 1080 MHz to 1300 MHz, 1 dB bandwidth: 1100 – 1270 MHz.

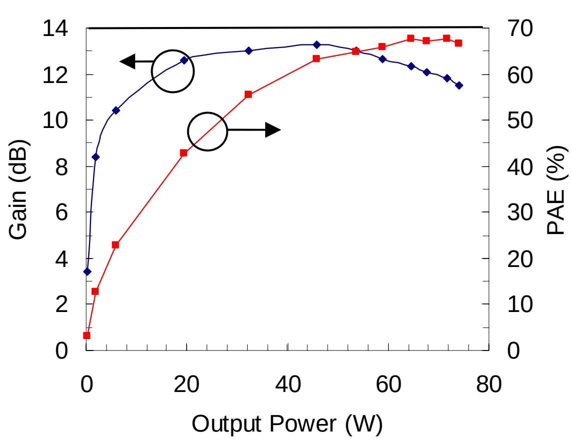

Fig. 6. Peak power and efficiency achievable for PA. At 1210 MHz, Drain Bias 30V, and Gate Bias 3V, Peak PAE is 67%, Peak Output Power is 74W.

Table 1. Performance comparison of the LD-MOS Class-E/F PA.

	This Work (Caltech)	**Long *et al*** (UCSB) [10]	**Le Gallou *et al*** (Alcatel) [11]	**Adahl *et al*** (Chalmers) [12]
Power	74 W	13 W	10 W	10 W
Gain	12 dB	14 dB	13 dB	13 dB
PAE	67%	58%	66%	66%
1-dB BW	170 MHz	N/A	>50 MHz (3dB)	50 MHz (3dB)
Class	ClassE/$F_{odd,2}$	Class D-1	Class F-1	Class E
Freq	1.22 GHz	1.0 GHz	1.5 GHz	1.0 GHz
Device	Motorola Si LDMOS MRF 284	Ericsson Si LDMOS PTF 10135	UMS Custom GaAs HBT	Motorola Si LDMOS MRF 282
Size	5 cm x 3.5 cm	6 cm x 20 cm	Confidential	10 cm x 10 cm

B. *Results of the 30W Class-A/B Power Amplifier*

A GaAs Class-A/B PA was designed, fabricated and tested (Fig. 7). The PA uses a Fujitsu FLL4001P-2 transistor in push-pull configuration. The drain voltage was set to 12V to achieve optimum performance.

Fig. 8 shows the frequency response of the amplifier centered at 1.24 GHz. The amplifier has a gain of 11dB with a 1dB bandwidth of 130MHz. The amplifier delivered 36W with a PAE of 69% (74% drain efficiency). This amplifier achieved excellent efficiency compared to the switching amplifiers in Table 1.

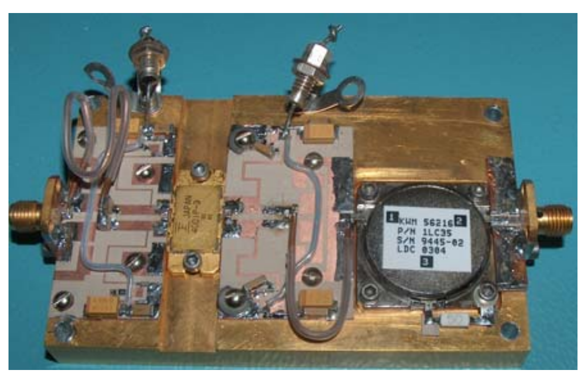

Fig. 7. Photograph of the GaAs Class-A/B 30W power amplifier.

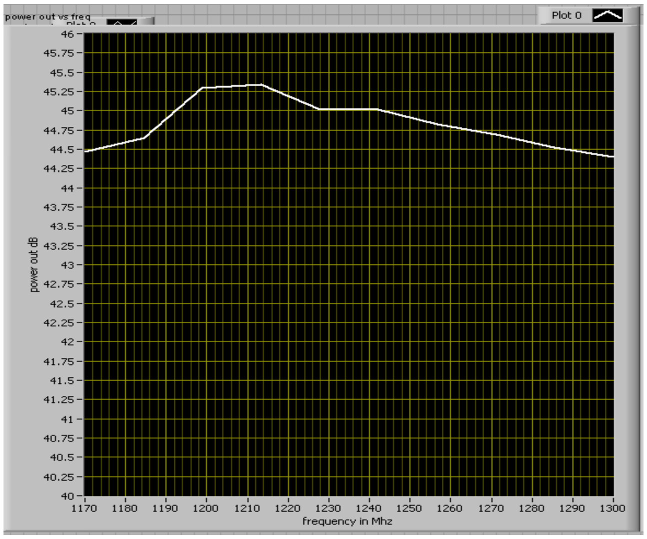

Fig. 8. Power output vs. frequency of the 30W Class-A/B PA.

C. *Results of the Integrated 30W & 70W T/R Modules*

We took a modular approach to implement the integrated T/R module. A common low power section drives either the 30W or the 70W power amplifiers. The low power section consists of a completely stand-alone 3W T/R module. The 3W T/R module includes the phase-shifter, attenuator, LNA, input switches and control logic. The integrated 30W T/R module brassboard using the Class-A/B PA is shown in Fig. 9. The 70W Class-E/F PA was also integrated into the T/R module in a similar construction. Both modules measure 7.9 x 2.6 x 1 inches with a mass of 500g. For our development, we traded a compact packaging for a more modular design.

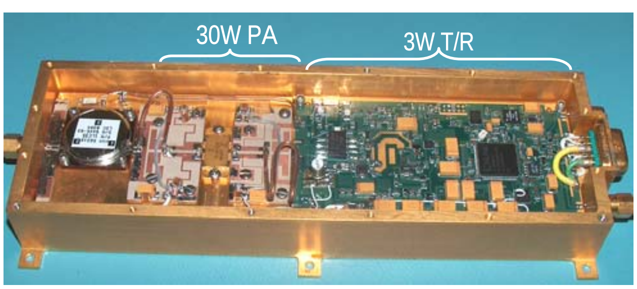

Fig. 9. Photo of the 30W T/R Module. The 3W T/R is the low power section which drives the PA.

The measured performance of the 30W and 70W T/R modules is summarized in Table 2. Since each T/R module uses the same 3W T/R module driver, both modules have identical receive characteristics. The 30W module achieved an overall module efficiency of 60% which includes the PAE of the PA plus circulator losses, and power for biasing the LNA, phase shifter, attenuator and FPGA. The 70W T/R module did not achieve the target output power. An output power of 45W was measured over a 50MHz bandwidth. This was due to the 3W drive level was not sufficient to efficiently drive the PA. Also a mismatch between the Class-E/F PA and the driver further degraded the output power and bandwidth. We plan to correct for this by developing a matched high-efficiency 5W driver amplifier to allow a sufficient drive level into the 70W PA.

Table 2. Measured results of the 30W and 70W T/R module. Performance exceptions are shown in blue.

PARAMETER	GOAL	MEASURED (30W T/R)	MEASURED (70W T/R)
Center Frequency	1.25 GHz	1.24 GHz	1.2 GHz
1dB Bandwidth	80 MHz	130 MHz	50 MHz
Peak transmit power	30 Watts	33.5 Watts	45 Watts
Efficiency	70%	74% drain eff 69% PAE 60% module eff	69% drain eff 65% PAE 58% module eff
Max duty cycle	10%	>10%	>10%
Transmit Gain	48 dB	50 dB	51 dB
Receive Gain	23 dB	23 dB	23 dB
Receive Noise Figure	<2.5dB	2.8 dB	2.8 dB
Phase Shifter	6-bit	6-bit	6-bit
Rx Third Order Intercept (Input)	>-19 dBm	-15 dBm	-15 dBm
Harmonics	-20 dBc	-40 dBc	-40 dBc
Spurious signals	-60 dBc	-60 dBc	-60 dBc
Input/Output VSWR	< 1.5:1	1.3:1	1.3:1
T/R Module Mass	100 g	500 g	500 g
T/R Module Size	2.5" x 1.5" x 0.5"	7.9" x 2.6" x 0.76"	7.9" x 2.6" x 0.76"

V. FUTURE WORK

We plan to further address miniaturization of the T/R module. A new layout of the module has been completed and we predict the mass of the next version will be reduced to 175g and the size will be reduced to 4.7" x 2.6" x 0.9". We also plan to develop a 5W Class-E/F driver amplifier to allow the Class-E/F PA to be driven at a higher level for optimal output power (>70W) and efficiency. The T/R modules will also undergo ambient and limited environmental testing to raise the TRL to 5.

VI. SUMMARY

Two high-efficiency, high power L-band T/R modules have been developed for use in future InSAR applications. A 30W T/R module using a GaAs Class-AB PA has demonstrated over 60% module efficiency. A 45W T/R module using an LD-MOS Class-E/F PA has demonstrated 58% module efficiency. Both modules exhibit excellent RF performance and meet nearly all requirements for an InSAR mission (exceptions are highlighted in blue in Table 2). Both T/R module designs have circuit models that match predicted and measured performance such that either design can be adapted to other power requirements.

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